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Temporal variations in the partial pressure and flux of CO_2 at ocean station P in the subarctic northeast Pacific Ocean

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ABSTRACT

The temporal variations in the partial pressure and air-sea flux of CO_2 in surface seawater at Ocean Station P (50° N 145° W) between August, 1973, and July, 1978, were investigated. In the summer months of 1973–1977, the evasion of CO_2 from the ocean to the atmosphere was less than 1 mM m^{-2} d^{-1} except for July of 1975 with a higher net flux of 1–2 mM m^{-2} d^{-1}. In the other seasons and also in the summer of 1978, a net sea-to-air CO_2 flux of about -3 mM m^{-2} d^{-1} occurred. The eastern subarctic waters around Station P was probably a small sink for CO_2 during the 5-year observational period with an average net sea-to-air flux of about -0.7 M m^{-2} yr^{-1}. The CO_2 exchange coefficient (K) was about 0.05 M m^{-2} μatm^{-1} yr^{-1} and the unidirectional CO_2 exchange rate was about 17 M m^{-2} yr^{-1}.

1. Introduction

The variations in CO_2 fluxes over the ocean are crucial for projecting the future level of atmospheric CO_2. A key parameter of the oceanic CO_2 system is the partial pressure of dissolved carbon dioxide, P_{CO_2}, in the surface ocean. The difference between the partial pressures of CO_2 in the surface seawater and in the overlying atmosphere defines areas of CO_2 source and sink over the ocean. Since the high-latitude waters are probably undersaturated with respect to CO_2 in the summer (Keeling, 1968), these oceanic areas could play an important role in the climate - CO_2 feedback processes by removing a large quantity of CO_2 from the atmosphere.

During the International Geophysical Years, a technique employing a non-dispersive infrared (NDIR) analyzer was developed for continuous shipboard determination of P_{CO_2} in surface seawater. Briefly, this technique was to measure the CO_2 concentration in a volume of air which has been equilibrated with the seawater pumped from the surface ocean into an equilibrator (Takahashi, 1961; Keeling et al., 1965; Kelley and Hood, 1971). The technique was applied to map the spatial distribution of oceanic P_{CO_2} (Keeling, 1968). A gas chromatographic method was used recently to study the seasonal variation of P_{CO_2} in the equatorial Pacific waters (Weiss et al., 1982) and in the North Atlantic Ocean (Takahashi et al., 1983).

The exchange of CO_2 between the surface seawater and the overlying atmosphere is regulated by the gradient of CO_2 partial pressures across the air-sea interface, the gas transfer velocity (or piston velocity) and the solubility of CO_2 in seawater. The transfer velocity characterizes the rate of CO_2 exchange between the air and the surface ocean and its value can be obtained by field measurement or in the laboratory (Liss, 1988). One field method for estimating the local short-term flux of CO_2 is to measure the vertical profile of the radon deficit in the surface ocean (Broecker and Peng, 1974). This method was used to determine the CO_2 flux at the BOMEX area of north Atlantic (Broecker and Peng, 1971) and at Station P (Peng et al., 1974). Other projects using this method included the GEOSECS program (Peng et al., 1979), the TTO program (Smethie et al., 1985) and others (Batrakov et al., 1981; Roos and Gravenhorst, 1984).

One laboratory method in determining the transfer velocity of CO_2 is derived by measuring directly the changes in the concentration of air CO_2 within a wind/wave tunnel under different wind stress conditions. A set of mathematical equations can then be developed to relate the wind speeds with the measured transfer velocities (Liss and Merlivat, 1986). This was the approach employed in the FOCAL program (Andrié et al., 1986; Oudot and Andrié, 1986; Oudot et al., 1987).

Besides the GEOSECS and the TTO programs, there are also some studies on the variability of oceanic CO_2 system in the subarctic Atlantic Ocean (e.g., Takahashi et al., 1983; Takahashi et al., 1985), the tropical Atlantic Ocean (Oudot and Andrié, 1989), the western Pacific Ocean (Fushimi, 1987; Inoue et al., 1987) and the Southern Ocean (Inoue and Sugimura, 1988). The seasonal variabilities of oceanic CO_2 system in the eastern Bering Sea are reported by Codispoti et al. (1982; 1986). In the eastern subarctic Pacific, only a few surveys on the CO_2 system in the surface seawater are available (Gordon et al., 1971; 1973; Takahashi, 1989). However, systematic observations of the carbon chemistry around this oceanic region have not been reported in detail.

This paper describes part of the results from the 1973–1978 Canadian Oceanic CO_2 Monitoring Program. One of its main objectives is to establish the temporal variations of the sea surface P_{CO_2} and the CO_2 fluxes in the eastern subarctic Pacific at Ocean Station P (50°N 145°W).

2. Measurements

Continuous shipboard measurements were made on board CCGS Quadra while the ship was on station at Ocean Weather Station P in alternate six-week intervals from August 1973, to July 1978. The observation were sparse in the first two years but more regular between 1976 and 1978. Flask samples of marine air were also collected in duplicate twice a week to obtain a time series on the background level of atmospheric CO_2 (Wong et al., 1984; Keeling et al., 1985).

For measurements of the oceanic P_{CO_2}, seawater was delivered by pump at a rate of 20 l min^{-1} from the sea chest, about 2 m below sea level, into an equilibrator situated at about 10 m above sea level. The relatively high pumping rate and the thermal insulation around the water pipes would maintain the temperature difference between the intake and the equilibrator to within ± 1°C under field conditions for most of the time. For each sampling cycle, temperatures of seawater both at the intake and in the equilibrator were recorded and their difference was used later to correct for the temperature effect on P_{CO_2}.

The equilibrator was modified from a design described by Keeling et al., (1965). Volumes of seaweter and enclosed air in the equilibrator were 20 litres and 10 litres, respectively. The enclosed air, which was being circulated in a loop of stainless steel tubings by a metal diaphragm pump, was sprayed with a constantly renewed supply of seawater from the intake. In similar shower-type equilibrators employed by other workers (Broecker and Tahahashi, 1966; Takahashi et al., 1970), water and air differing initially in CO_2 partial pressure by 20% can be equilibrated within 5 min. The analytical loop of the system included a mechanical cold trap with cooling coils at −50°C for moisture removal, a flowmeter and an URAS-II NDIR analyzer. A series of automated solenoid valves allowed time-sequence sampling of two working gas standards, marine air and air equilibrated with seawater. The complete sampling cycle took about 30 min. All the CO_2 measurements were initially expressed as mole fractions in parts per million by volume (ppmv). The precision of the measurements was about ± 1%.

The gas standards of CO_2-in-N_2 used in the analysis system were calibrated with the primary gas standards supplied by the Scripps Institution of Oceanograhy. Beginning in 1975, additional procedure to check for instrument linearity were also performed several times during each cruise. Four working gas standards were analyzed with the NDIR analyzer. The CO_2 concentrations of these secondary standards bracketed the range of values likely to be encountered during the cruise. A linear correlation analysis between the analyzer outputs and the CO_2 concentrations of the standards was performed. In most cases, the correlation coefficients were about 0.98.

Seawater at 1 m depth was sampled daily at 00.00 hours GMT for sea surface temperature (SST), salinity, and dissolved oxygen as parts of the routine oceanographic survey conducted by the Institute of Ocean Sciences. Other meteoro-

logical data required for the computation of air-sea fluxes were obtained from the weather records maintained by the Atmospheric Environment Service, Canada. These parameters, taken every three hours, included barometric pressure at sea level, wind speed, wet-bulb and dry-bulb temperatures.

3. Computations and data analyses

There was no automatic data logging system installed in the analyzer system. All the data from the analyzer's strip charts and other records were coded manually.

3.1. *Data selection*

The shipboard records for the equilibrium concentration of CO_2 in surface seawater exhibited great variability. When tracings were read from the strip charts, some extreme outliers or short-term fluctuations were excluded as unrepresentative. Such examples were caused by fluctuations of electric voltage during inclement weather or by contaminations from room air or the exhaust from the ship. When calculating the mean values of a given data set, we employed a two-step averaging procedure. Those data that lie beyond ± 2 standard deviations of the original mean value were again excluded. The selected data were subsequently used for calculating the reported mean values. This scheme removed about 4.6% of the total data for the seawater P_{CO_2}.

3.2. P_{CO_2} *in air*

For computation of the atmospheric P_{CO_2}, we used the flask-sample data reported earlier (Wong et al., 1984; Chan and Wong, 1990). The mole fractions of CO_2 in dried air were obtained by interpolating a smoothing spline fitted to the whole data set. This procedure would reduce the variabilities of the data (Chan and Wong, 1990). The P_{CO_2} in the atmosphere was computed using the interpolated mole fraction of CO_2, the barometric pressure, and the saturated water vapor pressure at sea surface temperature. All the P_{CO_2} values were assumed to be moisture-saturated at the air-sea interface.

3.3. P_{CO_2} *in seawater*

In computing the P_{CO_2} in surface seawater, the CO_2 mole fraction of the equilibrated air was adjusted to a moisture-saturated basis using the water vapor pressure in seawater at the in situ temperature. Values of ocean-surface salinity were interpolated from the daily observations which were fitted with a smoothing spline. Any change in P_{CO_2} due to temperature variation after sampling at the intake was corrected by the temperature dependence of CO_2 fugacity (Weiss et al., 1982). We used the equations by Weiss (1974) to convert all CO_2 mole fractions to values of fugacity assuming the air was moisture-saturated at the air-sea interface. After the adjustment, the fugacity values were converted back to values of CO_2 partial pressure for easy and direct comparison with other studies.

3.4. CO_2 *transfer velocity and flux*

The net flux of CO_2 across the air-sea interface, F, can be computed from

$$F = ks\,\Delta P_{CO_2}, \tag{1}$$

where k is the CO_2 transfer velocity, s is the solubility of CO_2 in seawater and ΔP_{CO_2} is the difference in CO_2 partial pressures between seawater and air, i.e., $P_{CO_2}(\text{seawater}) - P_{CO_2}(\text{air})$ (Keeling, 1968; Smethie et al., 1985; Andrié et al., 1986). The global distributions of k for 4 months are presented by Thomas et al. (1988). Sometimes the product ks is also referred to as the CO_2 exchange coefficient (K) and a world map of K is also available (Etcheto and Merlivat, 1988). The solubility of CO_2 in seawater at specified salinity and temperature can be calculated using the function of Weiss (1974). In Eq. (1), any chemical enhancement for the exchange of CO_2 in seawater is assumed to be negligible (Quinn and Otto, 1971; Goldman and Dennett, 1983).

The transfer velocity k of a given gas is a function of the wind speed and of the temperature through the Schmidt number Sc dependency (Liss and Merlivat, 1986; Jähne et al., 1987). Sc is the ratio of the kinematic viscosity of water to the molecular diffusivity of a given gas. For this study, we used the relation between the CO_2 transfer velocity, wind speed and sea surface temperature proposed by Merlivat and her coworkers (Andrié et al., 1986; Liss and Merlivat, 1986; Etcheto and Merlivat, 1988). The dependence of CO_2 transfer

velocity at 20°C on wind speed is given for three different wind regimes. These functions are

$$k = 0.17u_{10}, \quad \text{for} \quad u_{10} \leqslant 3.6, \tag{2}$$

$$k = 2.85u_{10} - 9.65, \quad \text{for} \quad 3.6 < u_{10} \leqslant 13, \tag{3}$$

$$k = 5.9u_{10} - 49.3, \quad \text{for} \quad u_{10} > 13, \tag{4}$$

where k is the transfer velocity (in cm h^{-1}) and u_{10} is the wind speed (in m s^{-1}) at 10 m above the sea surface.

In our computations, the effective wind speed was taken arbitrarily to be the observed value three hours before the actual P_{CO_2} sampling. The wind speed, which was observed at 28 m height, was normalized to speed at 10 m height according to the computing algorithm developed by Smith (1981; 1988). Briefly, his algorithm iteratively solved for the wind and temperature profiles which are in the form

$$u = (u_*/k)[\ln(z/z_0) - \psi_m] \tag{5}$$

$$\theta = \theta_0 + (\theta_*/k)[\ln(z/z_0) - \psi_t], \tag{6}$$

respectively, where u_* is the friction wind velocity, θ_* is the scaling temperature, z_0 is the surface roughness length, θ_0 is the extrapolated temperature at $z = 0$, $k = 0.4$ is the von Karman constant, and ψ_m and ψ_t are functions of stability which vanish in the neutral case.

From the u_{10} value, we computed the transfer velocity at 20°C from one of eqs. (2–4). This k value was then adjusted for the different sea surface temperature through the Schmidt number by assuming that k is proportional to $Sc^{-2/3}$ for $u_{10} \leqslant 3.6$ m s^{-1} and to $Sc^{-1/2}$ for higher wind speeds as suggested by Liss and Merlivat (1986). In calculating the molecular diffusivity, we used the relation between temperature and the molecular diffusivity of CO_2 as derived by Holmén and Liss (1984). The viscosity of seawater was computed according to the procedure used by Riley and Skirrow (1975). This procedure depends on the equations developed by Millero (1974) using values of distilled water by Korson et al., (1969).

4. Results

For presentation of the data, the calendar month is divided into four periods, i.e., days 1–8, days 9–16, days 17–24, and days 25–end of month, and the appropriate data in each period are

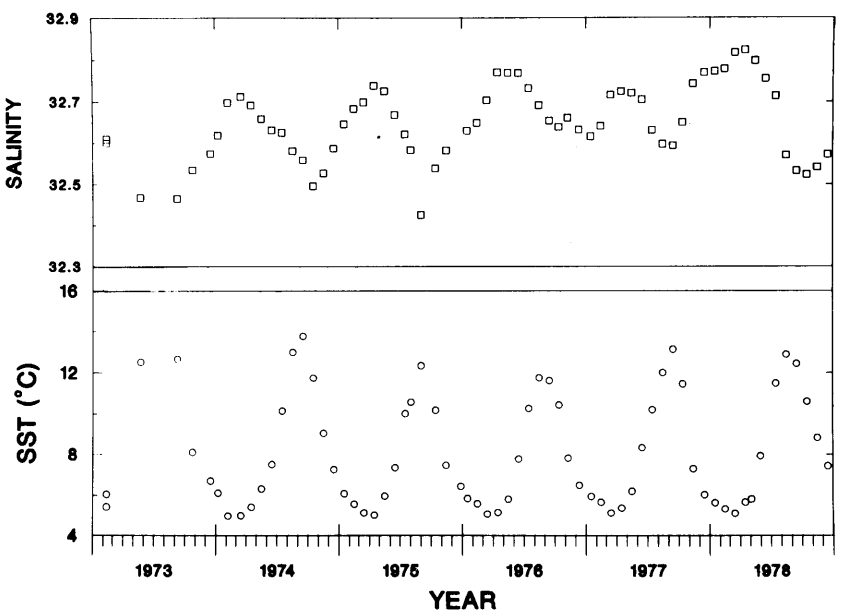

Fig. 1. Monthly averages of sea surface temperature (SST) and salinity sampled at Station P during 1973–1978.

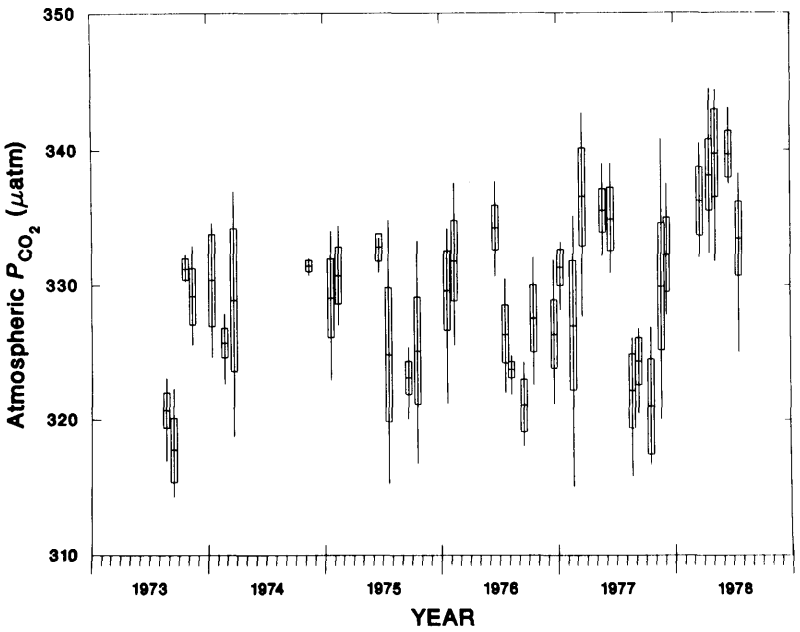

Fig. 2. Monthly averages of the partial pressures of CO_2 in the near-surface atmosphere at Station P during 1973–1978. The total air pressure is assumed to be saturated with water vapour at sea surface temperature. The central cross in the rectangle denotes the mean value while the top and the bottom of the rectangle represent the $\pm 1\sigma$ from the mean respectively. The vertical line passing through the rectangle shows the range of the data for a given month.

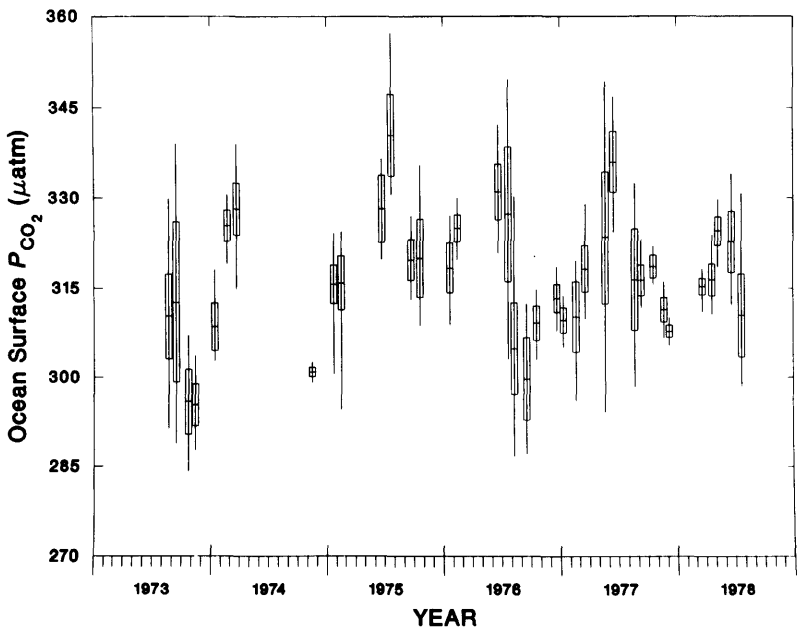

Fig. 3. Monthly averages of the partial pressures of CO_2 in surface seawater. The total pressure is assumed to include water vapour at saturation. The meaning of the rectangle and the vertical line are the same as in Fig. 2.

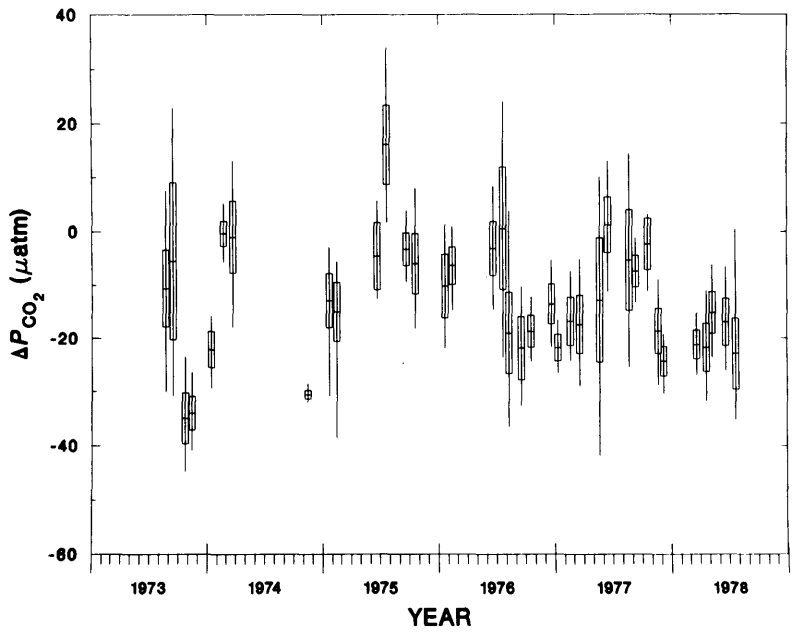

Fig. 4. The differences in the partial pressures of CO_2 in seawater and in air: $\Delta P_{CO_2} = P_{CO_2}(\text{sea}) - P_{CO_2}(\text{air})$. The meaning of the rectangle and the vertical line are the same as in Fig. 2.

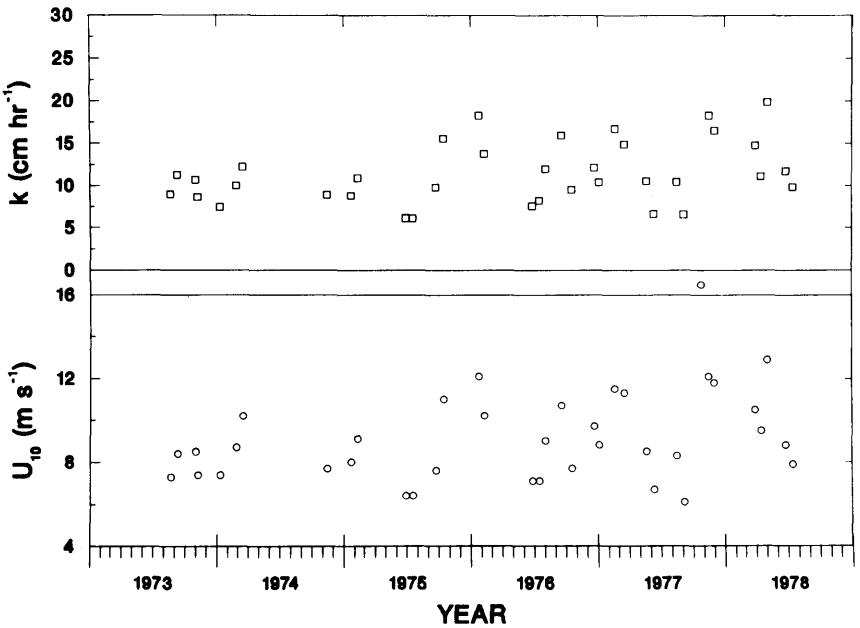

Fig. 5. (Bottom) Monthly averages of wind speed (u_{10}) at Station P adjusted to a 10 m height. The averages only included those values when P_{CO_2} measurements were also available. (Top) The computed transfer velocities of CO_2 (k) at the air-sea interface. Procedure for the computation is described fully in the text.

Table 1. *Averages of sea surface temperature (SST), seawater salinity, air temperature (T), mean sea level pressure (P), wind speed at 10 m height (u_{10}), CO_2 transfer velocity (k), and CO_2 exchange coefficient (K) at Station P from August 1973 to July 1978*

Date	SST (°C)	Salinity	T (°C)	P (kPa)	u_{10} (m s^{-1})	k (cm h^{-1})	K (M m^{-2} atm^{-1} d^{-1})
12–16 Aug 1973	12.2	32.470	11.5	102.6	7.5	9.6	96.8
17–21 Aug 1973	12.5	32.476	11.6	103.0	6.8	8.0	80.3
25–31 Aug 1973	12.5	32.465	12.4	101.9	7.7	9.0	101.4
1– 8 Sep 1973	12.6	32.466	12.6	100.9	9.4	13.9	141.3
9–16 Sep 1973	12.5	32.457	12.4	101.8	7.5	9.5	96.7
30–31 Oct 1973	8.9	32.496	7.0	102.8	8.5	10.7	122.0
1– 8 Nov 1973	8.7	32.499	6.9	102.4	7.2	7.6	91.1
9–13 Nov 1973	8.4	32.501	5.6	101.6	10.6	16.0	172.5
5– 8 Jan 1974	6.1	32.610	3.4	102.8	4.8	3.3	34.2
9–13 Jan 1974	6.0	32.625	4.8	101.1	9.6	11.4	150.2
19–24 Feb 1974	5.0	32.686	2.7	99.6	12.0	18.1	209.2
25–28 Feb 1974	4.8	32.719	2.3	100.1	6.8	6.6	83.0
1– 8 Mar 1974	4.9	32.712	3.4	101.6	11.8	16.0	204.5
9–16 Mar 1974	4.8	32.716	3.0	100.2	11.1	14.4	187.5
17–24 Mar 1974	4.8	32.721	5.5	102.2	10.0	12.1	160.8
25–31 Mar 1974	5.3	32.704	5.2	98.5	5.2	3.6	44.0
13–14 Nov 1974	9.2	32.497	7.3	102.6	7.7	8.9	102.8
14–16 Jan 1975	6.1	32.657	5.8	101.1	8.8	10.5	130.8
17–23 Jan 1975	6.1	32.657	7.0	100.1	8.8	10.5	130.8
26–28 Jan 1975	6.1	32.653	4.8	101.3	7.1	7.1	89.8
1– 6 Feb 1975	5.7	32.673	2.7	102.0	9.6	11.9	150.4
9–14 Feb 1975	5.7	32.689	3.1	100.6	8.9	10.5	133.5
24–24 Jun 1975	8.0	32.648	7.9	102.0	6.2	5.8	67.4
26–30 Jun 1975	8.0	32.647	8.3	102.4	6.4	6.1	72.2
1– 8 Jul 1975	9.5	32.634	9.9	102.7	4.8	4.0	33.6
13–16 Jul 1975	10.4	32.614	10.6	101.1	7.1	8.1	88.0
19–22 Jul 1975	10.2	32.618	10.8	101.0	6.0	5.5	62.0
25–30 Jul 1975	10.4	32.605	10.4	102.6	6.9	7.8	83.3
15–16 Sep 1975	12.5	32.480	12.2	102.3	7.5	9.5	96.7
17–24 Sep 1975	12.8	32.364	13.6	101.8	7.9	10.4	106.1
25–30 Sep 1975	11.3	32.490	11.7	101.2	7.2	8.6	90.1
1– 8 Oct 1975	10.8	32.497	9.9	100.5	11.1	17.5	182.6
9–16 Oct 1975	10.5	32.512	10.5	100.9	10.5	14.6	168.6
17–24 Oct 1975	9.0	32.596	8.5	101.6	9.8	14.0	152.9
25–27 Oct 1975	9.0	32.574	7.3	101.3	13.1	21.6	234.1
17–24 Jan 1976	5.7	32.641	5.9	101.2	12.0	18.2	208.5
26–31 Jan 1976	5.6	32.647	6.7	99.8	12.3	18.4	215.9
1– 8 Feb 1976	5.8	32.622	6.2	101.6	12.1	18.2	210.9
9–14 Feb 1976	5.7	32.636	5.3	100.8	8.5	9.4	123.8
21–24 Jun 1976	8.1	32.758	8.2	102.5	8.4	10.2	119.9
25–30 Jun 1976	8.6	32.785	8.0	102.2	6.4	6.3	71.9
1– 8 Jul 1976	9.5	32.759	9.6	100.3	6.0	5.6	62.1
9–16 Jul 1976	9.9	32.729	9.7	101.4	6.4	6.9	71.5
17–24 Jul 1976	10.1	32.736	10.2	101.3	7.8	9.2	104.6
25–31 Jul 1976	10.9	32.702	11.2	102.6	8.6	11.6	123.2

Table continued

Table 1—*continued*

Date	SST (°C)	Salinity	T (°C)	P (kPa)	u_{10} (m s^{-1})	k (cm h^{-1})	K (M m^{-2} atm^{-1} d^{-1})
1– 6 Aug 1976	11.4	32.702	11.6	102.4	9.0	12.0	132.4
14–16 Sep 1976	11.4	32.661	11.7	101.7	9.7	14.4	148.9
17–22 Sep 1976	11.2	32.650	11.1	100.8	11.0	16.3	179.8
8– 8 Oct 1976	10.5	32.647	8.9	101.1	6.4	6.6	71.4
13–16 Oct 1976	10.6	32.655	9.4	102.4	6.8	7.7	80.8
17–24 Oct 1976	10.4	32.635	10.0	101.4	8.7	12.3	125.9
7– 7 Dec 1976	7.0	32.633	5.9	101.5	9.5	12.1	147.1
10–16 Dec 1976	6.6	32.633	6.0	100.2	9.5	12.1	147.4
17–24 Dec 1976	6.3	32.632	6.4	99.6	9.2	11.7	140.3
25–31 Dec 1976	6.3	32.633	5.2	99.9	10.5	13.1	171.7
1– 8 Jan 1977	6.1	32.613	6.2	101.2	9.6	11.7	150.1
9– 9 Jan 1977	6.1	32.608	4.0	101.5	6.1	5.2	65.6
14–16 Feb 1977	5.8	32.643	6.1	100.3	11.5	16.1	196.3
17–24 Feb 1977	5.6	32.651	5.8	98.7	11.7	17.5	201.4
25–26 Feb 1977	5.4	32.681	4.7	100.7	9.3	11.4	143.4
7– 8 Mar 1977	5.1	32.688	3.4	99.5	12.5	20.7	221.3
9–16 Mar 1977	5.1	32.724	4.3	102.8	11.5	15.7	197.0
17–24 Mar 1977	5.2	32.709	4.3	101.7	10.3	12.0	167.7
25–28 Mar 1977	4.9	32.721	4.2	101.9	13.2	20.0	243.7
10–14 May 1977	5.8	32.714	5.3	101.1	9.9	12.5	157.6
18–24 May 1977	6.1	32.715	5.8	101.3	10.2	13.2	164.6
25–31 May 1977	6.9	32.707	6.8	101.2	5.1	3.5	41.2
1– 5 Jun 1977	7.4	32.738	7.1	101.4	6.0	5.3	62.7
9–16 Jun 1977	8.3	32.683	9.0	102.2	7.6	7.9	100.7
17–20 Jun 1977	8.7	32.679	9.2	101.1	6.4	6.4	71.9
2– 8 Aug 1977	11.1	32.577	11.9	101.6	9.7	13.6	149.2
9–16 Aug 1977	11.4	32.621	12.3	101.8	7.9	10.2	106.5
20–24 Aug 1977	12.5	32.609	13.1	100.6	8.7	11.9	124.9
25–31 Aug 1977	12.6	32.596	13.0	101.5	6.5	7.0	73.1
1– 7 Sep 1977	12.8	32.594	12.9	101.7	6.6	7.4	75.4
10–11 Sep 1977	13.3	32.571	13.7	102.5	4.6	3.1	28.4
25–26 Oct 1977	8.9	32.696	8.9	98.8	16.5	35.6	401.9
2– 8 Nov 1977	7.9	32.718	6.5	101.3	10.6	14.7	172.7
9–16 Nov 1977	7.4	32.733	5.7	100.0	11.7	17.9	199.5
17–24 Nov 1977	6.9	32.765	6.7	101.3	13.5	22.6	256.1
25–30 Nov 1977	6.9	32.756	6.9	100.1	12.2	17.9	212.0
1– 4 Dec 1977	6.8	32.748	4.4	101.3	11.8	16.5	202.5
27–31 Mar 1978	5.3	32.834	4.9	101.1	10.5	14.8	172.4
1– 8 Apr 1978	5.4	32.835	4.7	101.2	10.1	12.4	162.6
9–16 Apr 1978	5.5	32.826	4.9	102.6	9.9	12.2	157.7
17–24 Apr 1978	5.8	32.819	5.1	101.3	6.7	6.8	80.1
25–30 Apr 1978	6.1	32.810	5.8	100.7	11.5	15.5	195.9
1– 7 May 1978	5.9	32.815	6.2	101.8	12.9	19.9	229.9
20–24 Jun 1978	9.3	32.752	9.5	103.4	9.3	12.5	140.7
25–30 Jun 1978	9.8	32.744	9.1	102.7	8.3	10.6	116.6
1– 8 Jul 1978	10.2	32.732	10.5	101.6	7.2	8.4	90.4
9–16 Jul 1978	11.5	32.722	11.2	102.4	8.0	10.3	108.8
17–24 Jul 1978	12.2	32.718	12.6	102.9	9.4	13.8	141.4
25–31 Jul 1978	12.8	32.682	12.1	101.3	6.0	6.5	61.3

Table 2. *Averages of surface seawater P_{CO_2}, ΔP_{CO_2}, and CO_2 flux at Station P. The numbers enclosed in brackets are the 1σ and the number of observation respectively for each of the mean values*

Date	Sea surface P_{CO_2} (μatm)	ΔP_{CO_2} (μatm)	CO_2 flux (mM m^{-2} d^{-1})
12–16 Aug 1973	305.16(7.59; 108)	−15.8(7.32; 108)	−1.5(0.93; 106)
17–21 Aug 1973	314.54(4.49; 105)	−7.5(4.55; 106)	−0.6(0.59; 104)
25–31 Aug 1973	311.23(5.45; 60)	−7.4(6.28; 60)	−0.8(0.76; 60)
1– 8 Sep 1973	326.35(8.35; 81)	10.6(8.22; 81)	1.1(1.37; 82)
9–16 Sep 1973	305.00(9.01; 145)	−14.6(8.72; 144)	−1.6(1.27; 142)
30–31 Oct 1973	295.82(5.54; 27)	−34.9(4.70; 26)	−4.0(2.15; 28)
1– 8 Nov 1973	295.90(3.97; 180)	−34.1(3.14; 177)	−2.9(1.84; 188)
9–13 Nov 1973	293.96(2.44; 85)	−33.8(2.98; 85)	−6.0(3.58; 88)
5– 8 Jan 1974	310.43(4.59; 64)	−23.0(4.29; 64)	−0.8(0.75; 67)
9–12 Jan 1974	306.41(1.65; 61)	−21.2(1.79; 61)	−3.0(1.13; 61)
19–24 Feb 1974	324.12(3.55; 40)	−0.3(2.81; 39)	−0.1(0.83; 40)
25–28 Feb 1974	325.79(2.23; 70)	−0.3(1.94; 67)	0.0(0.15; 64)
1– 8 Mar 1974	327.30(3.67; 135)	−3.5(3.64; 139)	−0.8(0.80; 140)
9–16 Mar 1974	322.55(7.20; 131)	−4.2(9.89; 132)	−0.8(1.78; 132)
17–24 Mar 1974	329.87(2.53; 131)	−3.7(3.49; 132)	−0.7(0.58; 133)
25–31 Mar 1974	331.26(2.31; 79)	8.9(1.76; 80)	0.4(0.35; 77)
13–14 Nov 1974	300.87(0.81; 32)	−30.6(0.80; 33)	−3.1(1.53; 33)
14–16 Jan 1975	316.97(1.94; 22)	−13.1(4.89; 22)	−1.5(0.81; 21)
17–23 Jan 1975	316.96(1.74; 52)	−9.1(2.24; 53)	−1.1(0.55; 55)
26–28 Jan 1975	311.95(6.64; 53)	−18.5(6.73; 53)	−1.4(0.92; 52)
1– 6 Feb 1975	312.36(7.83; 44)	−20.9(7.22; 44)	−3.3(1.30; 45)
9–14 Feb 1975	317.02(2.56; 94)	−12.6(2.24; 94)	−1.7(0.42; 89)
24–24 Jun 1975	319.70(0.00; 1)	−12.6(0.00; 1)	−0.9(0.00; 1)
26–30 Jun 1975	328.82(5.30; 14)	−4.0(6.09; 14)	−0.4(0.64; 14)
1– 8 Jul 1975	343.78(10.27; 40)	11.6(8.98; 39)	0.2(0.22; 38)
13–16 Jul 1975	350.37(5.66; 18)	26.8(6.12; 18)	2.4(1.40; 18)
19–22 Jul 1975	338.38(3.00; 39)	18.3(3.10; 39)	1.0(0.49; 39)
25–30 Jul 1975	336.50(3.29; 40)	12.4(2.18; 39)	1.2(0.66; 42)
15–16 Sep 1975	321.97(4.41; 19)	−1.2(5.09; 19)	0.1(0.46; 19)
17–24 Sep 1975	319.18(3.47; 68)	−3.3(3.03; 67)	−0.4(0.34; 67)
25–30 Sep 1975	319.68(2.92; 37)	−3.5(2.51; 37)	−0.3(0.24; 36)
1– 8 Oct 1975	317.33(2.89; 42)	−5.0(3.57; 43)	−0.8(0.58; 43)
9–14 Oct 1975	314.21(2.34; 27)	−12.9(3.16; 26)	−1.5(0.99; 28)
17–24 Oct 1975	326.56(3.36; 23)	−3.5(3.21; 22)	−0.3(0.25; 21)
25–27 Oct 1975	332.54(7.39; 17)	3.9(7.30; 17)	0.7(1.58; 17)
17–24 Jan 1976	315.60(3.57; 113)	−15.3(4.59; 115)	−3.0(1.39; 113)
26–31 Jan 1976	320.85(3.15; 115)	−5.9(3.39; 116)	−1.2(0.99; 114)
1– 8 Feb 1976	324.40(2.68; 102)	−8.3(4.41; 102)	−1.8(0.95; 103)
9–14 Feb 1976	325.17(1.98; 111)	−5.4(2.19; 114)	−0.7(0.51; 114)
21–24 Jun 1976	332.84(4.33; 64)	−2.2(4.99; 63)	−0.2(0.51; 63)
25–30 Jun 1976	329.73(4.59; 106)	−3.6(5.40; 111)	−0.3(0.54; 106)
1– 8 Jul 1976	335.95(5.01; 180)	9.6(5.02; 181)	0.5(0.45; 175)
9–16 Jul 1976	328.16(6.90; 151)	0.1(6.02; 150)	−0.1(0.53; 150)
17–22 Jul 1976	316.55(8.77; 93)	−9.2(10.61; 93)	−1.2(1.82; 92)
25–31 Jul 1976	307.93(3.97; 47)	−18.2(3.52; 47)	−1.8(1.23; 49)
1– 6 Aug 1976	304.75(7.72; 128)	−19.0(7.71; 127)	−2.2(1.21; 127)

Table continued

Table 2—*continued*

Date	Sea surface P_{CO_2} (μatm)	ΔP_{CO_2} (μatm)	CO_2 flux (mM m^{-2} d^{-1})
14–16 Sep 1976	305.76(3.28; 19)	−18.3(3.24; 19)	−1.3(0.82; 19)
17–22 Sep 1976	297.40(6.50; 57)	−23.4(5.87; 56)	−3.6(1.43; 56)
8– 8 Oct 1976	305.10(0.00; 1)	−18.8(0.00; 1)	−1.3(0.00; 1)
13–16 Oct 1976	310.80(2.12; 81)	−18.9(2.63; 85)	−1.5(1.14; 83)
17–24 Oct 1976	307.95(2.85; 120)	−18.7(3.28; 121)	−2.4(2.26; 118)
7– 7 Dec 1976	314.78(1.90; 15)	−16.2(2.26; 15)	−2.4(0.50; 15)
10–16 Dec 1976	314.44(1.98; 48)	−13.3(3.49; 49)	−1.1(0.54; 49)
17–24 Dec 1976	313.69(2.11; 152)	−12.3(4.10; 150)	−1.7(1.35; 150)
25–30 Dec 1976	311.77(2.30; 113)	−14.7(3.25; 115)	−2.6(1.48; 110)
1– 8 Jan 1977	310.01(2.09; 87)	−21.2(2.29; 93)	−2.6(1.30; 87)
9– 9 Jan 1977	307.57(1.05; 19)	−24.7(1.24; 19)	−1.4(0.46; 19)
14–16 Feb 1977	311.28(1.31; 18)	−17.6(1.61; 17)	−3.4(1.05; 18)
17–24 Feb 1977	305.84(7.62; 30)	−17.2(5.97; 30)	−4.1(3.29; 30)
25–26 Feb 1977	317.08(2.03; 8)	−13.1(1.10; 8)	−1.9(1.22; 8)
7– 8 Mar 1977	319.70(3.04; 27)	−8.2(2.45; 27)	−2.0(1.32; 21)
9–16 Mar 1977	319.98(3.20; 122)	−17.5(6.09; 125)	−3.1(1.43; 120)
17–24 Mar 1977	316.18(1.78; 151)	−19.3(3.12; 152)	−3.2(1.29; 148)
25–28 Mar 1977	320.13(6.88; 66)	−16.3(5.87; 67)	−4.0(1.23; 67)
10–14 May 1977	304.60(13.08; 91)	−31.0(12.91; 91)	−4.4(2.11; 90)
18–24 May 1977	325.20(3.81; 140)	−10.9(4.20; 139)	−1.7(0.97; 138)
25–31 May 1977	329.05(8.13; 114)	−5.9(8.61; 114)	−0.5(1.10; 109)
1– 5 Jun 1977	334.49(6.12; 114)	−0.6(6.62; 114)	−0.2(0.40; 111)
9–16 Jun 1977	337.06(4.33; 172)	1.2(4.02; 169)	0.0(0.30; 166)
17–20 Jun 1977	336.32(4.93; 71)	3.6(5.34; 74)	0.1(0.34; 69)
2– 8 Aug 1977	304.99(5.86; 125)	−17.8(7.74; 126)	−2.6(1.80; 127)
9–16 Aug 1977	319.02(5.26; 139)	−4.9(5.03; 145)	−0.3(0.56; 140)
20–24 Aug 1977	325.31(3.94; 87)	6.8(4.69; 89)	0.8(1.00; 85)
25–31 Aug 1977	317.85(3.13; 120)	−4.1(3.35; 120)	−0.2(0.22; 115)
1– 7 Sep 1977	315.45(1.76; 119)	−8.2(2.56; 119)	−0.6(0.32; 113)
10–11 Sep 1977	322.30(2.12; 26)	−4.2(2.15; 26)	−0.1(0.10; 27)
25–26 Oct 1977	318.59(1.91; 24)	−2.4(4.84; 24)	−0.5(1.53; 24)
2– 8 Nov 1977	311.71(1.53; 133)	−19.8(3.65; 130)	−3.3(1.87; 123)
9–16 Nov 1977	311.40(2.04; 162)	−16.5(4.15; 158)	−3.5(1.79; 159)
17–24 Nov 1977	312.07(2.15; 167)	−19.8(5.51; 163)	−5.3(2.72; 170)
25–30 Nov 1977	309.43(2.00; 115)	−18.8(3.25; 117)	−4.0(1.62; 114)
1– 4 Dec 1977	307.67(1.03; 67)	−24.4(2.81; 69)	−5.0(0.88; 68)
27–31 Mar 1978	315.26(1.37; 100)	−21.3(2.74; 104)	−3.8(2.51; 103)
1– 8 Apr 1978	316.29(1.82; 175)	−20.9(2.14; 179)	−3.4(1.66; 177)
9–16 Apr 1978	315.17(2.05; 178)	−26.6(4.17; 180)	−4.3(1.14; 173)
17–24 Apr 1978	315.86(2.85; 174)	−22.0(3.14; 175)	−1.9(1.70; 182)
25–30 Apr 1978	320.55(3.05; 132)	−15.6(4.13; 135)	−3.1(1.08; 125)
1– 7 May 1978	324.51(2.37; 154)	−15.2(3.93; 148)	−3.5(1.51; 149)
20–24 Jun 1978	327.01(3.13; 87)	−14.3(3.66; 87)	−1.8(0.86; 90)
25–30 Jun 1978	319.69(4.05; 129)	−18.9(4.01; 130)	−2.1(1.15, 131)
1– 8 Jul 1978	315.52(4.69; 169)	−18.1(4.80; 170)	−1.6(1.14; 175)
9–16 Jul 1978	308.05(5.40; 162)	−26.8(3.66; 157)	−2.7(1.24; 162)
17–24 Jul 1978	308.04(6.27; 137)	−26.2(6.42; 137)	−3.5(1.36; 138)
25–31 Jul 1978	308.18(8.29; 103)	−18.0(12.31; 106)	−1.3(1.36; 110)

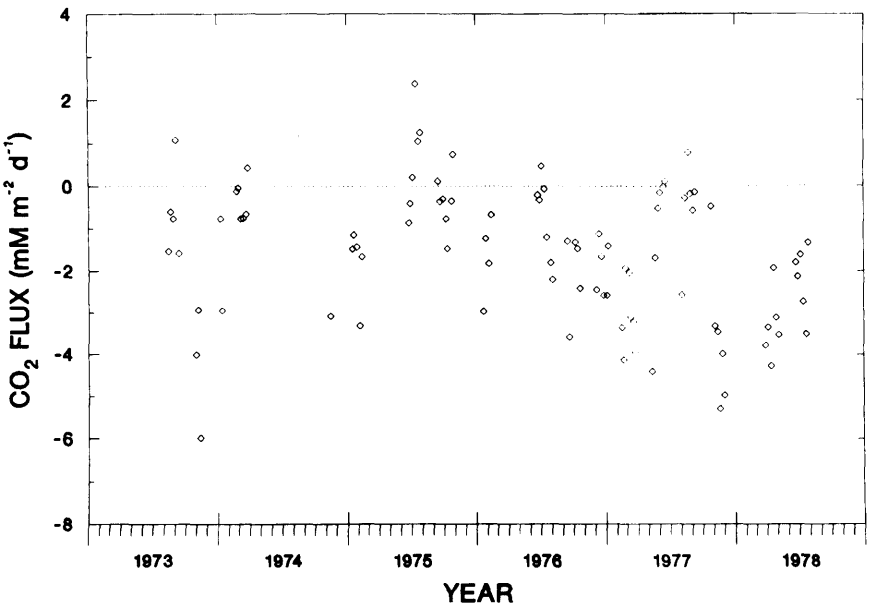

Fig. 6. The computed net fluxes of CO_2 at Station P during 1973–1978. Positive values represent evasions of CO_2 from the surface ocean to the atmosphere and negative values are invasions in the opposite direction.

averaged. Hereafter, these average values will be conveniently referred to as "weekly" means. Table 1 lists the "weekly" averages of several oceanographic properties and meteorological parameters observed during the 5-year period of the study. The table also includes the "weekly" averages of the CO_2 transfer velocity and the computed CO_2 exchange coefficient. Table 2 gives the means, one standard deviation from the means, and the numbers of observation for the oceanic P_{CO_2}, ΔP_{CO_2}, and the air-sea CO_2 flux for the same "weekly" periods.

Fig. 1 shows the monthly means of SST and salinity at Ocean Station P from 1973 to 1978. The monthly averages of atmospheric P_{CO_2}, oceanic P_{CO_2} for surface waters and ΔP_{CO_2} at Ocean Station P during the same period are depicted in Figs. 2–4, respectively. Variations in the wind speed at 10 m height (u_{10}) and the CO_2 transfer velocity are portrayed in Fig. 5, whereas the "weekly" means of the computed net fluxes of CO_2 are shown in Fig. 6.

5. Discussion

The subarctic waters of northeast Pacific are in an area affected by the North Pacific Drift and the Alaska gyre system. Ocean Station P is situated in the transit zone between these two current systems. The oceanographic properties at Station P are characterized by marked seasonal fluctuations (Tabata, 1961; 1989). The seasonal and annual variatons of these observations were discussed fully in various reports (Dodimead et al., 1963; Tabata, 1961; 1989). During the period of this study, the monthly means of surface seawater salinity (Fig. 1) varied between 32.5 and 32.8 with the high values occurred mainly in spring and the low values in autumn and winter. In general, the seawater in spring of 1977 was fresher and the seasonal amplitude of the monthly means was also smaller. For SST of the same period (Fig. 1), the seasonal cycle had an amplitude of 8°C, with a steep rise from a minimum in March of 5°C to a maximum of 13°C in September. In 1976, the monthly means of SST were lower than values from the same months in the other years. The interannual variability of SST was small: less than 1.5°C. There was a close correlation between the low SST and the low atmospheric CO_2 level observed in 1976 at Station P (Hanson et al., 1981).

At Station P, the surface mixed layer in winter sits on top of the permanent halocline which lies

between 100 and 200 m depth. After the last severe storm in April or May, the thermocline shoals up to a summer surface mixed layer of about 25 m or less (Tabata, 1961).

The concentrations of CO_2 in dried air sampled at Station P showed distinct seasonal cycles. Generally, most of the maxima occurred in May and the minima in late August with an average amplitude of about 14 ppmv (Wong et al., 1984; Chan and Wong, 1990). In comparison, the P_{CO_2} of moisture-saturated air were influenced considerably by the water vapour in the atmosphere. Several high values of around 340 μatm occurred in June and July of 1978, and the low values of about 320 μatm, mainly in September. Most of the winter P_{CO_2} values were around 325–335 μatm with considerable interannual variations (Fig. 2). In 1977 and 1978, the seasonal amplitude for the atmospheric P_{CO_2} was about 21 μatm.

The seasonal changes in surface seawater P_{CO_2} around the Station P area have not been studied extensively. The global ΔP_{CO_2} map of Keeling (1968) indicated a lack of data in the subarctic waters. The GEOSECS map (Takahashi et al., 1983) covered the margin at about 35°N (leg 1) and 175°W (leg 2) in the Pacific. Gordon et al. (1973) provided the coverage west of 178°W. Our study showed that at Station P, most of the P_{CO_2} values from surface seawater were about 290–340 μatm with the high values occurred mainly from May to July, and the low values, from August to October (Fig. 3). The average amplitude of the oceanic P_{CO_2} cycle of about 28 μatm is slightly larger than that of air P_{CO_2}.

There appeared to be interannual changes also in the maximum, minimum and the winter levels of P_{CO_2} in seawater. In 1976 and 1977, sharp drops in P_{CO_2} of 30–40 μatm occurred in a short period from mid-June to late August. During the summer of 1975, the seawater P_{CO_2} remained within a range of 20 μatm. The buildup seemed to be steady from the minimum of August 1976 to the maximum in late June 1977. However, the seawater P_{CO_2} remained at about 310 μatm from August 1977 until July 1978, when the shipboard P_{CO_2} measurements were terminated.

The P_{CO_2} features at Station P could be the results of several processes. Station P is situated at a point where the North Pacific Drift carrying the colder waters of high P_{CO_2} from the Oyashio Current, bifurcates into the Alaskan Gyre and the California Current (Dodimead et al., 1963). The waters at Station P include occasional incursions of productive coastal waters and warmer waters from the south. Another oceanographical factor might be the interannual shift of the mixed layer depth at Station P (Tabata, 1989). The thickness of the surface mixed layer formed each year determined the total amount of CO_2 available for air-sea exchange and summer removal by photosynthesis.

For seawater with constant total alkalinity and constant total inorganic carbon ($\sum CO_2$), the temperature coefficient with respect to P_{CO_2} is about 4.5% $°C^{-1}$ (Gordon and Jones, 1973; Weiss et al., 1982; Copin-Montegut, 1988). Similarly, the magnitude of P_{CO_2} also varies with the in situ salinity (Weiss et al., 1982). However, the increase in the observed surface-ocean P_{CO_2} at Station P from spring to summer are lower than the increase of P_{CO_2} due solely to the seasonal changes in SST and salinity. An example of these differences in the observed and the SST- and salinity-corrected values of P_{CO_2} is illustrated in Fig. 7. It plots the variations in the observed fugacity of surface-ocean CO_2 from 1975 to 1977 and the fugacity corrected only for the effects of both SST and salinity on CO_2 fugacity. In essence, the latter case assumes an abiotic ocean without change in the chemical composition of seawater. The temperature and salinity dependencies of CO_2 fugacity used for the corrections in Fig. 7 are derived by Weiss et al. (1982). These two empirical relations are only valid for seawaters of constant $\sum CO_2$ and constant total alkalinity.

As mentioned in Subsection 3.3, CO_2 fugacity was calculated as an intermediate step in the computation procedure. At Station P, the total alkalinity and $\sum CO_2$ in surface seawater in mid-February of 1975 remained relatively constant (Table 3). The CO_2 fugacity in the mixed layer at this time was adopted as the initial value in computing the fugacities in the hypothetical abiotic ocean. Calculations were carried out using the initial fugacity and the values of SST and salinity observed on the same day and also on the next sampling day to obtain the corrected fugacity. This new value was reset as the initial fugacity for the next daily increment and the procedure repeated.

The difference between the two curves in Fig. 7 presumably shows the magnitude of the effects of additional factors, other than SST and salinity, on

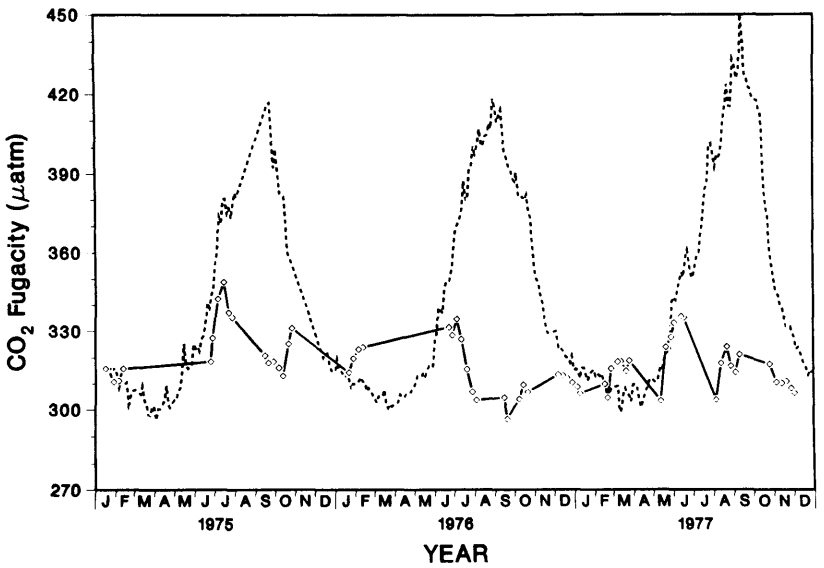

Fig. 7. The effects of changes in both temperature and salinity on the surface seawater P_{CO_2} at Station P. The solid curve (—) connects the "weekly" averages of the observed oceanic CO_2 fugacity. The broken curve (– –) represents the corrected values computed from the initial fugacity value at mid-February 1975 and the observed time series of SST and salinity at Station P. These corrections use the two empirical equations on the temperature and salinity dependences of CO_2 fugacity derived by Weiss et al., (1982). It is assumed that the water in mid-February 1975 were affected by the observed seasonal changes in both temperature and salinity without changes in its chemical composition.

the changes in seawater P_{CO_2}. In spring, the increase in phytoplankton production (Parsons and Lalli, 1988) would remove some of the CO_2 in seawater. From July to October, the large differences in P_{CO_2} between the observed and the corrected values are probably caused by the intense photosynthesis together with the sinking of detritus below the mixed layer. During the winter months with the deepening of the surface mixed layer, the P_{CO_2} in the surface ocean would build up again because of the decreasing photosynthetic utilization, mixing with the CO_2-rich subsurface water, and uptake of CO_2 from the atmosphere by the cooled surface waters. All these conditions allow the actual P_{CO_2} in surface seawater during February and March to be slightly higher than the corrected values.

The hypothesis that the differences between the two curves in Fig. 7, especially for the summer months, are mainly the result of intense photo-

Table 3. *Oceanic properties of surface seawater from Station P in early 1975; the total alkalinity, TAlk, are calculated from the SST, salinity, phosphate, silicate and the P_{CO_2} values*

Date	SST	Salinity	PO_4	NO_3	SiO_4	$\sum CO_2$	P_{CO_2}	TAlk
	(°C)		(μM kg^{-1})				(μatm)	(μeq kg^{-1})
17 Jan	5.8	32.656	1.38	13.8	17.6	2039	312.6	2216
9 Feb	5.8	32.678	1.35	13.8	20.8	2030	317.4	2203
16 Feb	5.7	32.700	1.30	13.6	20.7	2039		
26 Feb	5.5	32.679	1.51	14.0	20.5	2046		

synthesis could be inferred by comparing the probable removal of CO_2 with the production of O_2 or the estimate of new primary production. For example, in the mixed layer at Station P, the range of O_2 new production is about 4–12 M O_2 m^{-2} yr^{-1} (Thomas et al., 1990). Assuming a typical Redfield ratio of 138/106 for the oxygen to carbon conversion, the O_2 values would represent CO_2 uptakes of about 3–9 M m^{-2} yr^{-1} (or about 8–25 mM m^{-2} d^{-1}). The CO_2 uptake could also be obtained by using the ^{14}C primary production and a new to regenerated production ratio of 0.24 for the subarctic Pacific waters in August (P. Wheeler, per. comm., cited in Thomas et al., 1990). Recent estimates of primary production are about 600–1000 mg C m^{-2} d^{-1} in the subarctic Pacific (Miller et al., 1988) or about 550–850 mg C m^{-2} d^{-1} in August 1985 measured at Station P (C. S. Wong, unpublished data). From these primary production data, the range of new production is estimated to be about 11–20 mM CO_2 m^{-2} d^{-1}, similar to the values calculated from the O_2 data.

The values of new production estimated above might be compared with the probable CO_2 removal calculated from the difference between the observed and the corrected fugacities (Fig. 7). For the case in August, the P_{CO_2} values for the assumed abiotic ocean average about 430 μatm (Fig. 7), the atmospheric P_{CO_2} and K are respectively about 321 μatm and 113 μM m^{-2} μatm^{-1} d^{-1} (Table 4). Multiplying ΔP_{CO_2} with K gives a net flux of about 12 mM m^{-2} d^{-1}. Subtracting the observed net flux of about -1 mM m^{-2} d^{-1} (Table 4), the difference in CO_2 fluxes attributed to photosynthesis in the mixed layer is then about 13 mM m^{-2} d^{-1}, which is within the range estimated by using the O_2 or primary production data.

Most of the ΔP_{CO_2} values at Station P were below zero (Fig. 4). In our study, there were small supersaturations of 10–20 μatm in July of 1975, and less than 10 μatm in September 1973, March 1974, July 1976 and June-August 1977. The undersaturation in January–March for 1974 and 1976 were less than -10 μatm. While the few data in October–November 1973 showed an undersaturation of about -34 μatm, the values from October to December of 1976–1977 were about -17 μatm. All values between March and July of 1978 were below -15 μatm.

Our ΔP_{CO_2} results compare reasonably well with the other studies. Except for two weeks in July 1975, the supersaturations in summer are slightly less than the +15 ppmv reported by Gordon et al. (1973) for their July–August cruise. The undersaturations in March–April agree with the spring 1969 values of -10 to -20 ppmv near Station P observed on the TRANSPAC expedition of the CNAV ENDEAVOUR (Gordon et al., 1971). Our results also fall within the ΔP_{CO_2} distribution prepared by Tans et al. (1990). Their colour map shows a mean value of -20 to -40 μatm for the January to April period and a mean value of 0 to +10 μatm for the July to October period around the Station P region.

The wind velocities normalized to 10 m height observed during the study period (Fig. 6) also agreed well with other published reports (Dodimead et al., 1963). There were some low values of about 5–7 m s^{-1} in July and fairly strong wind of 12–13 m s^{-1} in the autumn and the winter seasons. An average wind speed of 12 m s^{-1} at Station P was obtained by Peng et al. (1974) during their CO_2 flux measurements in January–February, 1972.

The computed transfer velocities of CO_2 at Station P (Fig. 5) for the study period ranged from an average of 6 cm h^{-1} (or about 1.5 m d^{-1}) in the summer months to 20–30 cm h^{-1} (or 4.8–5.5 m d^{-1}) in the winter of 1977. Peng et al. (1974) obtained for their 1972 winter measurements an average value of 3.6 m d^{-1} for Rn (or 5 m d^{-1} for CO_2), which is within the range of our results for winter. In his study of the oxygen cycles at Station P, Emerson (1987) estimated that the transfer velocity for O_2 in summer is 2 ± 1.0 m d^{-1}, which when converted for CO_2, is about 0.8–2.5 m d^{-1}. From 1975 to 1978, the average transfer velocity was about 3 m d^{-1}, about the same value for Pacific Ocean between 40°N and 60°N obtained during the GEOSECS program using the radon method (Broecker and Peng, 1984).

In their studies of air-sea exchange of gases, Broecker and his co-workers (Broecker and Peng, 1982; 1984) expressed the net CO_2 flux as the unidirectional gas exchange rate or invasion rate. Their definition of the gas-exchange rate, I, may be related to the net CO_2 flux, F, in eq. (1) as:

$$I = FP_{CO_2}(\text{air})/\Delta P_{CO_2}. \quad (7)$$

Table 4 gives the monthly means of atmospheric

Table 4. *Weighted monthly means of atmospheric P_{CO_2}, ΔP_{CO_2}, net CO_2 flux (F; eq. (1)), CO_2 gas-exchange rate (I; eq. 7), and CO_2 exchange coefficient (K)*

Month	P_{CO_2}(air) (μatm)	ΔP_{CO_2} (μatm)	F (mM m^{-2} d^{-1})	I	K (M m^{-2} atm^{-1} d^{-1})
Jan	329.9	−16.1	−1.9	39.2	130.6
Feb	329.3	−8.6	−1.5	57.6	161.3
Mar	332.3	−9.7	−1.9	65.8	177.6
Apr	338.5	−21.8	−3.2	48.9	149.1
May	336.9	−14.8	−2.5	57.1	148.3
Jun	336.1	−5.2	−0.7	44.2	83.1
Jul	329.0	−8.5	−1.1	43.6	85.4
Aug	321.6	−9.1	−1.0	35.9	113.1
Sep	320.6	−7.1	−0.8	36.9	96.4
Oct	326.7	−14.4	−1.7	37.5	171.1
Nov	329.9	−23.9	−4.0	55.1	172.3
Dec	327.3	−15.0	−2.5	53.6	161.8

P_{CO_2}, ΔP_{CO_2}, F, and I computed according to eq. (7). The weighted average of I for the entire study period at Station P was about 17 M m^{-2} yr^{-1}. This value was within the range of the global CO_2 gas-exchange rate of 20 ± 3 M m^{-2} yr^{-1} estimated by the natural radiocarbon method or about the same as the 16 M m^{-2} yr^{-1} obtained by the radon deficit method (Broecker and Peng, 1974; 1982; 1984; Peng et al., 1979).

The monthly averages of the CO_2 exchange coefficient, K, (Table 4) follow the variations of the observed wind speeds and the CO_2 solubility in seawater, i.e., low values in the summer and high values in the winter. For the study period at Station P, the weighted annual mean of K is about 0.05 M CO_2 m^{-2} μatm^{-1} yr^{-1}. This is fairly close to the range of 0.03–0.037 M m^{-2} μatm^{-1} yr^{-1} given in the map prepared by Etcheto and Merlivat (1988).

Since the flux of CO_2 across the air-sea interface is partially governed by the sign and magnitude of ΔP_{CO_2}, the surface seawater at Station P could be a weak CO_2 source in July to August of 1975 to 1977 and predominantly a CO_2 sink in the other months. Most of the "weekly" averages of net CO_2 fluxes were between 0 and −5 mM m^{-2} d^{-1} (Fig. 6). For the sampling period, the oceanic area found Station P was likely a weak CO_2 sink of which the net sea-to-air flux was about −0.7 M m^{-2} yr^{-1}.

Tabata (1989) suggests that the interannual variabilities of SST, salinity, and dissolved oxygen in the surface waters at Station P are reflected in the surrounding area within a few to several hundred kilometres. Similar condition probably applies to the oceanic P_{CO_2} in the surface seawaters near Station P. This may be supported partly by the P_{CO_2} values from the trans-Pacific cruises in spring reported by Gordon et al. (1971). In this case, the temporal variation in the gas exchange of CO_2 in the eastern subarctic Pacific waters around Station P may differ from that of other oceanic areas in the high northern latitudes. In the subarctic North Atlantic, the surface ocean is likely an intense sink for atmospheric CO_2 during the summer months and a weak to neutral sink in the other seasons (Takahashi et al., 1983; 1985). Similar situation prevails in the Bering Sea and the northwest subarctic Pacific where the summer depression of P_{CO_2} in the surface seawater may exceed 100 μatm (Kelley and Hood, 1971; Gordon et al., 1973; Codispoti et al., 1982; 1986; C. S. Wong, unpublished data). These strong summer CO_2 sinks seem to differ with the weak to neutral summer sink for the eastern subarctic Pacific waters. This difference is demonstrated visually in the colour map prepared by Tans et al. (1990).

6. Conclusions

The surface seawater P_{CO_2} at Station P from 1973 to 1978 were about 290–340 μatm with the high values occurred mainly from May to July, and the low values, in the late summer and autumn.

There appeared to be interannual variabilities in the levels of P_{CO_2} in seawater. The summer value in 1975 averaged about 340 μatm while the mean summer value in 1978 was about 325 μatm.

The differences in P_{CO_2} between the ocean surface and the overlying air suggested that the oceanic area surrounding Station P is probably a weak or neutral source in summer and a net sink during the other seasons.

For 1973–1978 at Station P, the weighted mean of the CO_2 exchange coefficient (K), i.e., the product of the CO_2 transfer velocity and the CO_2 solubility in seawater, was about 0.05 M m^{-2} μatm^{-1} yr^{-1}.

In July of 1975, 1–2 mM m^{-2} d^{-1} of CO_2 outgassed from the ocean to the atmosphere.

About 3 mM m^{-2} d^{-1} of CO_2 transferred from the atmosphere to the ocean in the other seasons and also in the summer of 1978.

The unidirectional gas-exchange rate of CO_2, as defind by Broecker and Peng (1982), was about 17 M m^{-2} yr^{-1} for the same 5-year period at Station P.

The net sea-to-air flux of CO_2 at Station P during the study period averaged about -0.7 M m^{-2} yr^{-1}.

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